Investigation of Transient Forces Produced by Gases Expelled from Rapidly Heated Surfaces

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Abstract. A torsional impulse balance has been developed as a new diagnostic tool to study fundamental processes in laser-surface interactions. The impulse balance has been designed and tested with a robust calibration system to measure impulsive forces with resolution as low as 1 nano-Newton-second. A simple technique has been developed to accurately determine the force as a function of time from the motion of the nano-impulse balance system (NIBS). This technique will be useful in examining the transient responses of photon-surface interactions. Initial ablation measurements using anodized aluminum plates at vacuum and with various background gases are presented.

INTRODUCTION

Considerable work has been done in the past to understand and model the fundamental processes between photons of various energies and a wide range of materials. [1] Of particular interest are the transient forces due to processes of laser ablation and gas desorption from rapidly heated surfaces. Several techniques exist to measure the amount of material and the velocity at which it is expelled from a surface, such as time-of-flight mass spectrometry. With respect to the transfer of momentum, direct measurements of the transient forces can lead to a better understanding and characterization of the efficiency of the time dependent force that is produced under different configurations. For example, a wide variety of physical processes are included within the scope of ablation such as sputtering, vaporization, ionization, and gas desorption. The conditions under which each physical process may occur and the parameters which control each process can be studied using time resolved force measurements. To this end, a torsional impulse balance has been developed as a new diagnostic tool to study fundamental processes in laser-surface interactions. [2] The impulse balance has been designed and tested with a robust calibration system to measure impulsive forces with resolution as low as 1 nano-Newton-second (nNs). A simple technique has been developed to accurately determine the force as a function of time from the motion of the nano-impulse balance system (NIBS). This technique will be useful in examining the transient responses of photon-surface interactions.

Of all of the possible laser-surface interactions, focus is placed on the gas desorption and ablation effects with application to microscale devices. Historically, mechanical actuation in microdevices has been provided by electromagnetic or electrostatic forces; however, pressure-driven micro-actuation can in theory produce significantly (10^2 – 10^4 times) greater force per unit volume than possible with electrostatic or electromagnetic systems. [3] This may be demonstrated by using laser-induced, rapid heating of a surface to desorb gas molecules, where the momentum carried by the desorbing molecules would exert a pressure force on the heated surface.

There are two main goals in this experimental study. The first goal was the development of an impulse balance capable of obtaining time accurate force measurements with 1 nNs resolution. Proof of principle is provided for time accurate force measurements on the order of 0.1-1 sec and paves the way for improvements to provide time resolution on the order of microseconds. The second goal was to demonstrate the impulse balance's ability to measure ablation forces from the interaction of a laser beam with a sample material surface. A variety of materials have been used in the experiments to determine the possibility of creating small, efficient actuators that may be used in microscale devices. Experimental tests using an anodized aluminum plate will be presented in this work.

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GAS DYNAMICS OF ABLATION

An impulse is created from the pressure exerted by the desorbing or ablated molecules leaving a rapidly heated surface. The impulse is given by the integral of the ablative pressure, P_{ab}, multiplied by the area illuminated by the laser, A, over the period of surface temperature increase, t'.

$$I = \int_{t=0}^{t=t'} P_{ab} A dt \tag{1}$$

In this case, the ablative pressure is given by

$$P_{ab} = (-dn_S/dt) m \overline{C'_{ab}} \tag{2}$$

where n_s is the surface number density removed by the ablation mechanism and m is the surface material molecular weight. The parameter $\overline{C'_{ab}}$ is the average thermal speed of the ablation molecules given as the average over a half-Maxwellian as

$$\overline{C'_{ab}} = \sqrt{\pi k T_S / 2m} \tag{3}$$

where T_s is the surface temperature after the laser pulse. Although this is a time varying temperature, a measure of the temperature maximum can be given by

$$T_S = T_O + 2\left(\frac{\eta E}{KA}\right)\sqrt{\frac{\kappa}{\pi t'}} \tag{4}$$

where T_o is the initial surface temperature, η is the laser energy coupling coefficient for the surface, E is the laser pulse energy, K is the material thermal conductivity, and κ is the material thermal diffusivity.

EXPERIMENTAL SET UP

The NIBS was installed in a 41 cm diameter x 122 cm long, stainless steel vacuum chamber fitted with a 450 L/sec turbomolecular pump capable of maintaining pressures of approximately 2 x 10^{-6} Torr. For this study, impulse delivery to the NIBS is accomplished by directing a laser pulse at the target through a view port on the chamber. Calibration of the NIBS is provided by supplying a potential difference to the Electrostatic Force Calibration System (EFCS), which consists of an aluminum comb assembly described in detail by Selden and Ketsdever. [4] As shown in the experimental setup in Fig. 1, the power supply for the EFCS was attached to a pulse generator capable of delivering ±3500 V with a 20 ns rise time and a variable DC pulse width (minimum of 60 ns). The output of the pulse generator was sent directly to the EFCS assembly in the chamber where the applied voltage to the EFCS could be used to calculate the actual time-dependent force applied to the NIBS.

The motion of the NIBS was measured using an LVDT, which was connected to either a 16 or 24-bit data acquisition system. The 24-bit system used was limited to a sampling rate of 60 Hz, and the 16-bit system was capable of sampling at 333 kHz. Currently, the LVDT and data acquisition units limit the time response of the NIBS to approximately 0.01 sec. Significant improvement in the NIBS time response is necessary to investigate the impulse shape for ablation plumes and is currently being investigated. However, this study provides a proof of principle to demonstrate the NIBS ability to provide time resolved impulse data at the microsecond timescale.

The raw data obtained by the LVDT is denoised through either the Fourier [5] and/or wavelet transform [6] methods and is then used to derive the total impulse that was imparted to the NIBS. In the simplest case, for $\tau \ll T$, the total impulse may be derived from the maximum deflection. However, the real interesting details of the impulse or force applied are the time resolved characteristics. The Time-Resolved Impulse Measurement (TRIM) process is derived from the equation of motion for the NIBS. In this case, the force applied as a function of time is simply related to the addition of the position, velocity and acceleration components, which are scaled by the spring constant K, damping coefficient C, and the moment of inertia I, respectively as shown schematically in Fig. 2.

For the preliminary experiments described here, a Nd:YAG laser is used with a wavelength of 1064 nanometers and a pulse energy of 50 mJ. The pulse width of the laser is approximately 5-7 nanoseconds. The laser beam passes directly into the vacuum chamber through a quartz window, where it illuminates the target material. A number of parameters are controllable such as the spot size, which allows control of the fluence or power density on the surface.

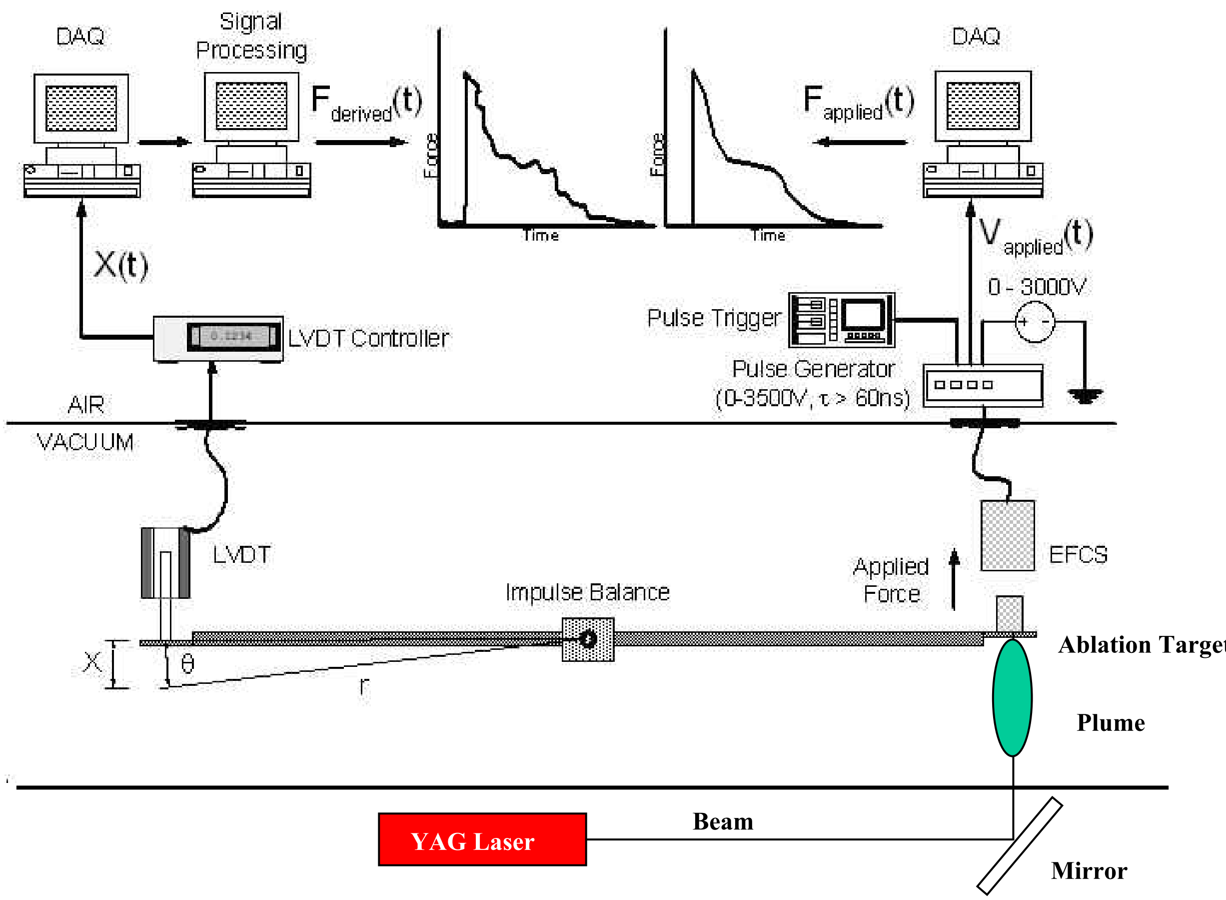

FIGURE 1. Experimental set up for time resolved impulse and laser ablation measurements.

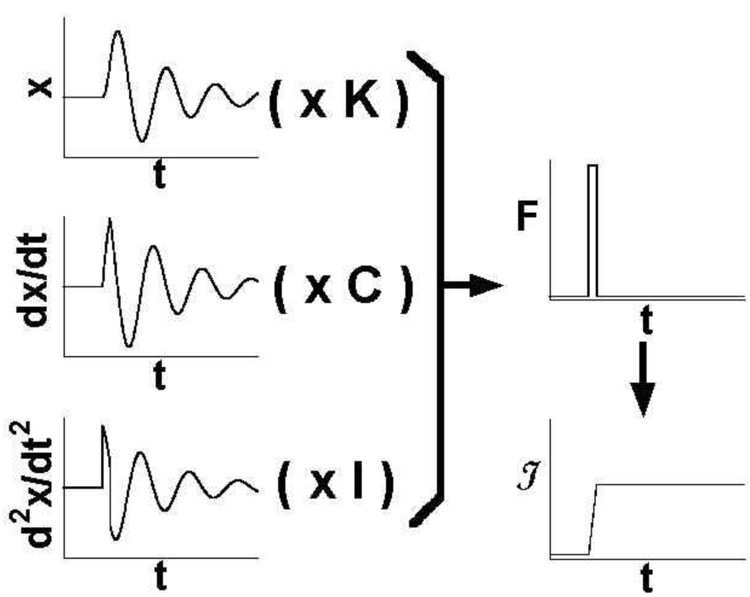

FIGURE 2. Schematic representation of the process for deriving the time-varying impulse or force from the balance's deflection and its derivatives.

RESULTS

NIBS time resolved force measurements

Figure 3 shows a time varying force applied to the thrust stand which might resemble that produced by a laser ablation mechanism. For this case, the force was delivered to the impulse balance through the EFCS. The derived force obtained from the NIBS position versus time data reproduced the actual applied force reasonably well. Many of the differences in the time varying force have been linked to limitations in the time resolution of the LVDT conditioning unit. As shown in Fig. 3, the applied and derived impulses are nearly identical and compare to within 1.9%. The reproducibility of the results for a variety of arbitrary impulses has been demonstrated elsewhere by D'Souza and Ketsdever. [2]

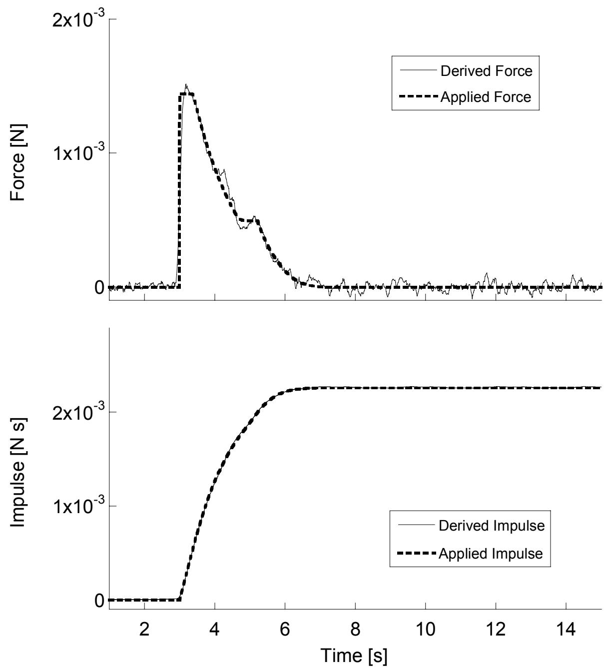

FIGURE 3. Plots of the applied and derived forces as a function of time for an arbitrary impulse and the corresponding applied and derived total impulses.

Surface Ablation

Initial proof of concept studies using the NIBS as a diagnostic tool for the ablation of surface materials being irradiated by laser beams have focused on using commonly available black anodized aluminum plates. The anodized surface provides a layer of material that is more likely to absorb the incident photons than an untreated aluminum material. Still, the reflectivity of the anodized surface can be quite high. Using the Nd:YAG laser in its 1064 nm configuration, no ablation effects or impulses were observed for unfocused or expanded beams. For the unfocused beam, a spot size of 3mm diameter corresponds with an estimated fluence of 400 mJ/cm^2. Using a single bi-convex lens to focus the beam to a spot size of approximately 1 mm diameter resulted in significant ablation of the anodized layer. The resulting fluence was estimated to be approximately 3.0 J/cm^2.

A set of tests was conducted for the 1 mm diameter beam to examine the impulse produced by surface ablation as a function of the number of shots on a particular site on the material in different ambient environments. The purpose of these tests was to examine the effectiveness of multiple shots on a particular site and the effect various gases may have on the impulse produced. Loss of bulk anodized material was expected to be the dominant mechanism in this case. The anodized layer was approximately 38±13 μm in thickness. It was experimentally verified that only the anodized layer (and not bulk aluminum) would ablate at the laser fluence used in this study.

With each shot on the anodized aluminum surface, less potential ablatant remains for the subsequent pulses. As a result, a decrease in the impulse produced is expected with each laser pulse.

Figure 4 shows the results of several laser pulses on the same location of the anodized layer in a low background pressure (5.0 x 10^{-6} Torr) environment. The deflection of the stand, and thus the impulse produced, is a maximum for the first laser shot and decreases as a function of the number of laser pulses as expected. Figure 5 shows the results of several laser pulses on an anodized aluminum surface. The data in Fig. 5 is obtained by combining data as in Fig. 4 with a detailed calibration analysis of the impulse balance using the EFCS. Each data point for a given laser shot represents the laser interacting with a different section of the material sample. In general, the repeatability of the results is quite good indicating that the anodized layer is relatively uniform.

The tests were repeated in air, helium and argon gas at 720 Torr. For each gas 3 to 4 target sites were used. For each target site, three pulses were delivered. Figure 6 provides a compiled view of several tests with the error bars representing the standard deviation of at least three runs. It is interesting to note that for first shots on a target site, the cases in vacuum produced slightly less impulse than those in a gas environment. On the second and third shots, there is much less variation between the results in different gases and vacuum. This indicates that there may be some differences in the formation of shock structures produced by the ablating gas expanding into vacuum and into a nearly 1 atm background for the case where the most ablatant is expelled from the surface (i.e. the first laser pulse). For subsequent pulses, the amount of gas generated by further ablation is significantly lower, as indicated by Fig. 4, which may negate the differences seen for the first pulse.

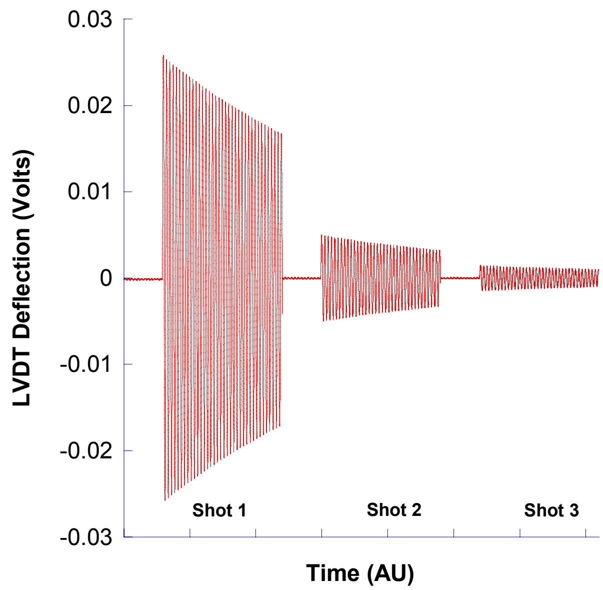

FIGURE 4. NIBS deflection from the ablation of an anodized aluminum surface as a function of the laser shot at a given site.

CONCLUSIONS

A diagnostic tool capable of measuring impulses with 1 nNs resolution has been developed. A proof of principle demonstration of the NIBS ability to provide time resolved impulse measurements has been completed. The ablation results demonstrate the feasibility to effectively measure the impulses due to laser-surface interactions, although system improvements are required for accurate time resolved data for laser ablation mechanisms. Through the variation of parameters such as wavelength, spot size, fluence, material and ambient environment, a robust data set can be collected to investigate a range of laser-surface interactions and the transition between them. Such a data set could be extremely useful in validating the development of laser-surface interaction models.

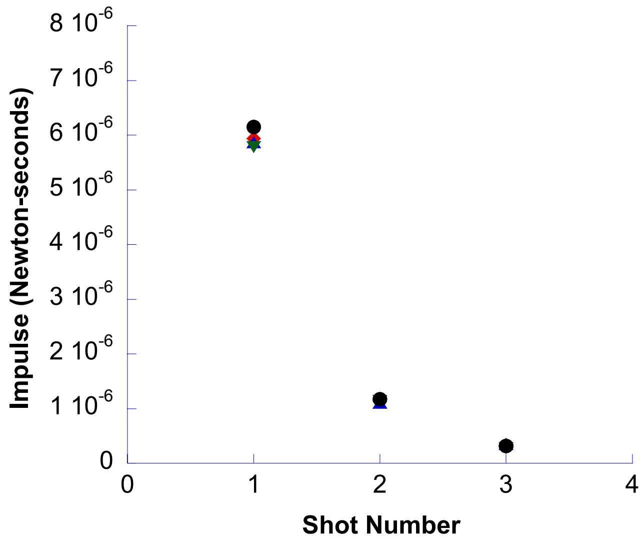

FIGURE 5. Impulse as a function of the number of laser pulses at a particular material site in a vacuum environment.

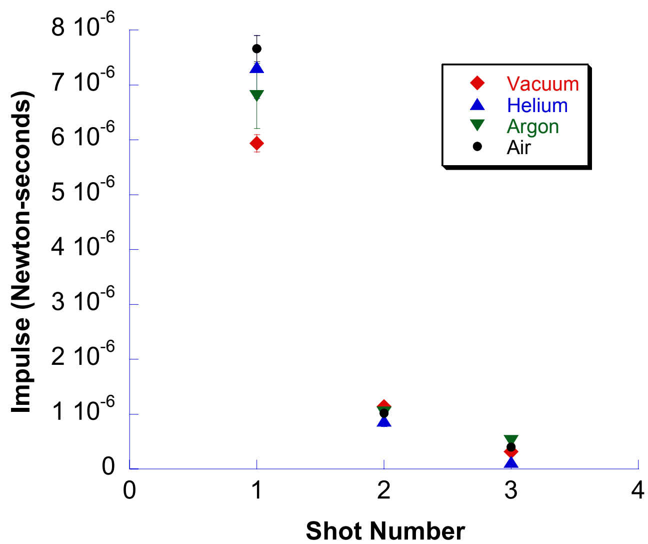

FIGURE 6. Impulse as a function of the number of laser pulses at a particular material site in various environments.

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